Systematic Effects in CMB Polarization Measurements

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The cosmic microwave background polarization is rich of cosmological information complementary to those from temperature anisotropies. Linear polarization can be decomposed uniquely in two components of opposite parities, called E and B. While E mode allows measurement of cosmological parameters in a way independent from temperature, B mode allows to detect the primordial gravitational waves produced during inflation, and thus to determine its energy scale. However, measuring CMB polarization is complicated by foregrounds, whose polarization is poorly known, and by systematic effects, which mainly affects B mode measurement because of its low level. As an example, we show here the effect of beams uncertainty on polarization measurement in the case of the Planck HFI instrument, and how we can correct for it.

1 Introduction

Temperature anisotropies have now been detected and measured by many experiments, most recent results confirming the Gaussianity of fluctuations, detecting the presence of acoustic peaks in the angular power spectrum of fluctuations and demonstrating the spatial flatness of the Universe. This provides compelling evidence that the primordial perturbations indeed have been generated during an inflationary period in the very early Universe. The next challenge is now to precisely measure the polarization anisotropies.

Polarization of cosmic microwave background is produced at the end of recombination period by Thomson scattering of CMB photons by electrons of the cosmic fluid. The gradient of fluid speeds induces quadrupole around electrons, causing emission of linearly polarized light. Linear polarization can be decomposed into two scalar fields on the sphere, distinguished by their parity properties: E mode is defined to have an even parity, while B is odd. Their interest lies in the difference in physical origins of these two modes: E mode can be produced by both scalar and tensor modes of primordial density fluctuations, while B mode can only be produced by tensor

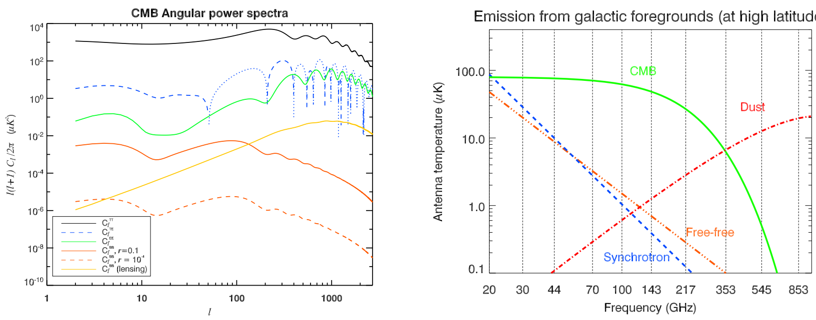

Figure 1: *Left:* Angular power spectra of temperature anisotropies and E and B mode of polarization. The two contributions from B mode are separated: tensor mode peaks at $l \sim 90$ while lensing contribution peaks at $l \sim 1000$. The tensor mode is shown for two different levels of initial tensor to scalar ratio, $r = 0.1$ and $r = 10^{-4}$. *Right:* Electromagnetic spectra of intensity of the different foregrounds.

fluctuations. The former, being produced by the same fluctuations as temperature anisotropies, allows as well the measurement of cosmological parameters, though it is more sensitive and has different directions of degeneracy. The concordance of cosmological parameters obtained from temperature anisotropies and E mode polarization would be an important test of the cosmological model and, combining both data, could increase their precision.

On the other hand, the B mode allows the direct detection of the gravitational waves (or the tensor modes), expected to be produced during the inflation era. If so, the level of the tensor mode is linked with the energy scale of inflation, for example in the slow-roll approximation, by the relation: $E_{\rm inflation} = 2 \cdot 10^{16} \times (\frac{r}{0.1})^{1/4}$ GeV, with r the initial tensor to scalar ratio which can be extracted from B mode measurement. B mode can also be produced by the gravitational lensing of CMB photons by large scale distribution of matter on the way from last scattering surface to us: the polarization pattern is distorted, so that a fraction of E mode is transformed into B mode.

The first detection of CMB polarization at one degree angular scale, at a level compatible with predictions of the standard cosmological scenario, has been announced by Kovac et al [1], while an upper limit of 8.4 μK for the E mode polarization signal at a sub-degree scale ($l \sim 200$) was established earlier by Hedman et al [2]. More recently, the WMAP team has obtained a measurement of the temperature-polarization correlation compatible with expectations on small scales, and bearing on large scale the signature of unexpectedly early reionization. No significant constraint on B modes exists yet. The Planck mission, with its full sky coverage and its polarized detectors in the frequency range 30-353 GHz, will be the first experiment able to constrain significantly these B modes, and hence to measure them on very large scales.

The measurement of CMB polarization is complicated by its low level compared to temperature anisotropies, making it highly sensitive to both foregrounds, discussed in the next section, and various systematic effects. As an example, we will expose the problem of the beam uncertainty for polarization measurement.

2 Foreground polarization

The expected level of CMB polarization is of the order of a few μK for E mode and around 0.1 μK for B mode. The foregrounds may very well contaminate maps of polarization. Two main origins of galactic emission are foreseen around the maximum emission of CMB: thermal emission of dust at high frequency, which polarization has recently been measured by Archeops at 353 GHz up to a degree of 20% in the galactic plane; and synchrotron radiation at low frequency, which is expected to be polarized up to 20%. With a plausible intensity of a few tenth of μK,

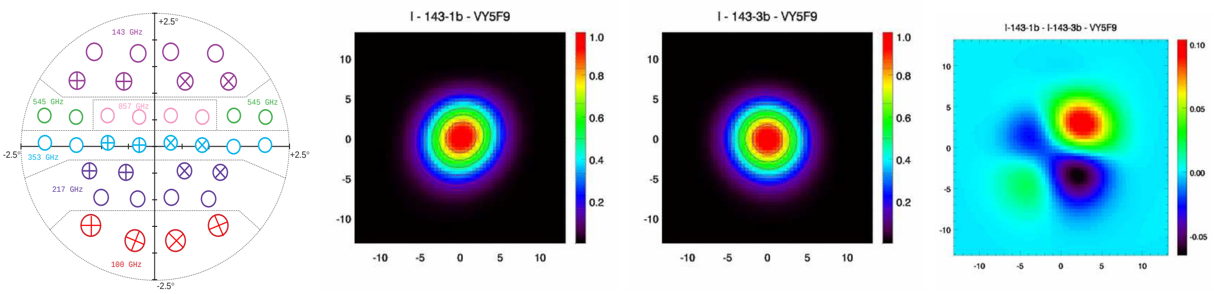

Figure 2: *Left:* Focal plane of the Planck High Frequency Instrument. *Center:* the beams computed for two horns, elongated in different directions. *Right:* the difference between the two beams of two different horns, which is up to 10% of the beam peak.

the polarized emission of these two sources easily dominates the CMB B mode. The distinction between foregrounds and CMB can be done through the difference in electromagnetic spectrum of the sources.

3 Systematic effects from beams

The weakness of the signal to measure makes the B mode particularly sensitive to various systematic effects. Beside usual systematic effects occurring in CMB experiments, such as $1/f$ noise, a whole class of them is specific to polarization, as its measurement involves the differences of signals. Indeed, linear polarization is characterized by two Stokes parameters, Q and U, defined as the differences of intensity through two polarizers at 90 degrees one from the other ($0°$ and $90°$ for Q, and $45°$ and $135°$ for U). Any differences between detectors combined to measure Q and U may result in a spurious polarization measurement, usually by transforming E mode into B mode or temperature anisotropies into both E and B polarization, as $T \gg E \gg B$.

The Planck High Frequency Instrument will measure polarization using Polarization Sensitive Bolometers (PSB) associated by pair inside one horn, each measuring the intensity for one direction of polarization. The difference of the signal from two PSB inside one horn thus gives a combination of Q or U in the frame of the focal plane. In order to get both Q and U in the sky reference frame, we need to combine the measurements from two horns.

An electromagnetic simulation of the optical system of Planck, including the telescope and the horns, done by V. Yurchenko [3], shows that the beams of the horns are elliptical (see Fig. 2). The difference between beams of different horns is then up to 10% of the beam peak, while the difference of intensity beams of the two detectors within the same horn is less than 0.5%.

We have estimated the effect of such beams on the measurement of CMB polarization power spectra by Monte-Carlo, using these simulated beams, on plane maps with a scanning strategy realistic for Planck. The power spectra of temperature and E mode are recovered with an error less than 0.1%, while the B mode is biased by a spurious polarization mainly coming from a E mode leakage, but also from a temperature leakage. The spurious B signal overcomes the CMB signal from $l \sim 300$ and the lensing B mode from $l \sim 700$ (see Fig. 3).

However, it is possible correct for this effect by estimating the bias induced by the beams difference if we have a precise enough knowledge of them: we can use the recovered temperature and E mode maps as input sky and simulate the instrument using the *known* beams. The output of this simulation contains some B mode, not present initially, which is an estimation of the observed spurious B mode (see Fig. 4). The efficiency of this correction strongly depends on how well the beams are known. As an example, if we approximate the beams by asymmetric two dimensional Gaussians, which are up to 2% different from the exact beams, the estimation of the spurious B mode is too low, making the correction inefficient.

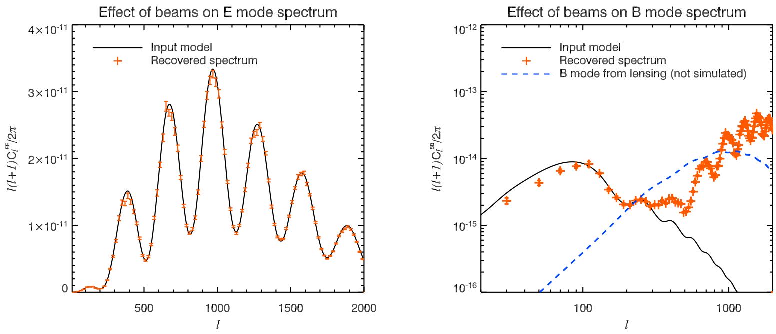

Figure 3: Recovered polarization power spectra with realistic simulated beams (see text and figure 2). E mode is recovered with a precision 0.1%, while B mode is affected at low angular scales by a temperature and E mode leakage due to beam differences.

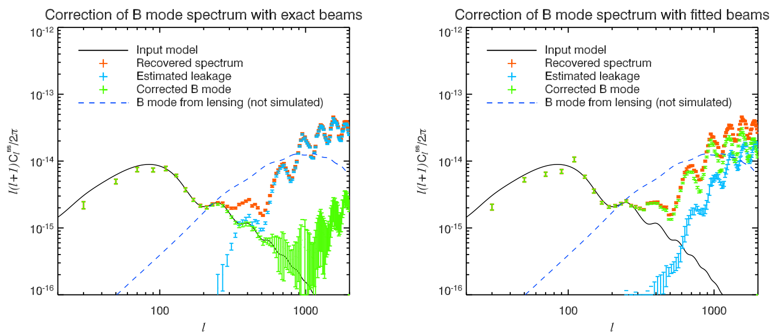

Figure 4: Correction of the B mode using exact beams (*left*) or Gaussian fit of the beams (*right*) with the method described in the text.

4 Conclusion

Measuring the faint CMB polarization signal is challenging because of the sensibility to various contaminations: astrophysical, as the foregrounds may overcome the CMB signal, and instrumental, because of the differential nature of the polarization. We have shown here the effect on polarization power spectra measurement due to differences in the beams, using realistic simulations for Planck. Other systematics are possible and important for polarization measurement with Planck, such as the relative calibrations or the time constants of bolometers. Specific methods have to be developped to take these effects into account and correct for them, particularly for the B mode power spectrum reconstruction.

References

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